

SNSN-323-63
January 27, 2011

Belle time-dependent gamma measurements

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The Belle experiment has measured the CKM angle γ in a variety of ways. In this paper, we focused on the recent progress of time-dependent γ analysis and the related measurements in Belle.

PRESENTED AT

6th International Workshop on the CKM Unitary Triangle,
University of Warwick UK, 6-10 September 2010

1 Introduction

The phenomenon of CP violation that is observed in high energy physics experiments is explained by a irreducible complex phase in the CKM matrix[1] in the Standard Model. The phase can be derived from measurements of the three angles and sides of the Unitarity Triangle. The angles are called as $\alpha = \text{Arg}[-(V_{td}V_{tb}^*)/(V_{ud}V_{ub}^*)]$, $\beta = \text{Arg}[-(V_{cd}V_{cb}^*)/(V_{td}V_{tb}^*)]$ and $\gamma = \text{Arg}[-(V_{ud}V_{ub}^*)/(V_{cd}V_{cb}^*)]$.

The angle γ is the least well determined among all angles. In the time-dependent γ measurement of $D^{(*)}\pi$, at first CP violation phase 2β is appeared in the $B\bar{B}$ mixing process and γ arised from followed two decay paths: Cabibbo favored decay (CFD) and doubly Cabibbo suppressed decay (DCSD) into a final state. The time-dependent decay rate is given by

$$\begin{aligned} P(B^0 \rightarrow D^{(*)+}\pi^-) &= \frac{1}{8\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} [1 - C \cos(\Delta m \Delta t) - S^+ \sin(\Delta m \Delta t)], \\ P(B^0 \rightarrow D^{(*)-}\pi^+) &= \frac{1}{8\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} [1 + C \cos(\Delta m \Delta t) - S^- \sin(\Delta m \Delta t)], \\ P(\bar{B}^0 \rightarrow D^{(*)+}\pi^-) &= \frac{1}{8\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} [1 + C \cos(\Delta m \Delta t) + S^+ \sin(\Delta m \Delta t)], \\ P(\bar{B}^0 \rightarrow D^{(*)-}\pi^+) &= \frac{1}{8\tau_{B^0}} e^{-|\Delta t|/\tau_{B^0}} [1 - C \cos(\Delta m \Delta t) + S^- \sin(\Delta m \Delta t)], \end{aligned} \quad (1)$$

where Δt is the difference between the decay-time of the signal B and other B , τ_{B^0} is the average neutral B meson lifetime, Δm is the $B^0 - \bar{B}^0$ mixing parameter, and $C = (1 - R^2)/(1 + R^2)$. S^\pm are given by

$$S^\pm = \frac{2(-1)^L R \sin(2\beta + \gamma \pm \delta)}{(1 + R^2)}, \quad (2)$$

where R is the ratio of the magnitudes of the DCSD and CFD, L is the orbital angular momentum of the final state(1 for $D^*\pi$ and 0 for $D\pi$), and δ is the strong phase difference of the CFD and DCSD.

2 $D^{(*)}\pi$ time-dependent CP analysis

The time-dependent CP violation analysis with fully reconstructed $D^{(*)}\pi$ events from a data sample of $386 \times 10^6 B\bar{B}$ pairs had performed by Belle[2]. The used decays are $D^{*+} \rightarrow D^+\pi^0$ or $D^0\pi^+$ followed $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^0 \rightarrow K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^-$ and $K_S^0\pi^+\pi^-$ ($K_S^0 \rightarrow \pi^+\pi^-$). Determination of the flavor of B meson opposite to CP side of B meson is used leptons, pions and kaons which are not associated with CP side B meson. Tag-side interference is taken into accounts introducing a small asymmetry when daughter particles from hadronic decays such as $D^{(*)}\pi$ are

used for the flavor tagging, due to the same CP violating effect[3]. The results are

$$\begin{aligned}
S^+(D^*\pi) &= 0.050 \pm 0.029(stat) \pm 0.013(syst), \\
S^-(D^*\pi) &= 0.028 \pm 0.028(stat) \pm 0.013(syst), \\
S^+(D\pi) &= 0.031 \pm 0.030(stat) \pm 0.012(syst), \\
S^-(D\pi) &= 0.068 \pm 0.029(stat) \pm 0.012(syst),
\end{aligned} \tag{3}$$

where the errors are statistical and systematic error, respectively.

The time-dependent CP violation analysis with partially reconstructed $D^*\pi$ from a data sample of $657 \times 10^6 B\bar{B}$ pairs had updated by Belle[4]. The measurement required fast pion(π_f) and slow pion (π_s) candidates. Three kinematic variables, p_δ, p_\parallel and p_\perp are defined and the cut are applied to reject backgrounds. In the boost the π_f into the partially reconstructed D^* frame, p_\parallel and p_\perp are defined parallel and the transverse components of the momentum of the π_s along with the opposite direction to π_f . The p_δ is defined as $p_\delta \equiv |p_{\pi_f}| - |p_{D^*}|$, where $|p_{D^*}|$ is magnitude of momentum for D^* which reconstructed by energies of B meson and π_f . Three categories of background source are defined: $D^{*\mp}\rho^\pm$, correlated background originated from inclusive D^* decay, uncorrelated background which includes everything else. The fractions are determined from (p_δ, p_\parallel) two dimensional fit. The flavor tagging is used by requiring a high momentum lepton in the event. This helps reducing continuum background of $e^+e^- \rightarrow q\bar{q}$, where $q = u, d, s$ and c . The result is

$$\begin{aligned}
S^+(D^*\pi) &= 0.057 \pm 0.019(stat) \pm 0.012(syst), \\
S^-(D^*\pi) &= 0.038 \pm 0.020(stat) \pm 0.010(syst).
\end{aligned} \tag{4}$$

3 $R_{D^{(*)}\pi}$ measurements with $D^*\pi^0$ and $D_s^{(*)}\pi$

It is difficult to determine R_{D^*} from B^0 decays because the DCSD amplitude is small compared to the contribution from mixing followed CFD, $B^0 \rightarrow \bar{B}^0 \rightarrow D^{*+}\pi^-$. Using available branching fraction measurements, $R_{D^*\pi}$ can be expressed as

$$R_{D^*\pi} = \sqrt{\frac{\tau_{B^0}}{\tau_{B^+}} \frac{2\mathcal{B}(B^0 \rightarrow D^{*+}\pi^0)}{\mathcal{B}(B^0 \rightarrow D^{*-}\pi^+)}}. \tag{5}$$

The decay $B^+ \rightarrow D^{*+}\pi^0$ is searched with a data sample of $657 \times 10^6 B\bar{B}$ pairs by Belle[5]. The obtained branching fraction is $\mathcal{B}(B^+ \rightarrow D^{*+}\pi^0) = [1.2^{+1.1}_{-0.9}(stat)^{+0.3}_{-0.9}(syst)] \times 10^{-6}$. The upper limit is $\mathcal{B}(B^+ \rightarrow D^{*+}\pi^0) < 3.6 \times 10^{-6}$ at 90% confidence level. This result can be used to set an upper limit on the $R_{D^*\pi}$,

$$R_{D^*\pi} < 0.051(90\%C.L.). \tag{6}$$

If we assumed SU(3) flavor symmetry, also $R_{D^{(*)}\pi}$ is given by

$$R_{D^{(*)}\pi} = \tan \theta_C \frac{f_{D^{(*)}}}{f_{D_s^{(*)}}} \sqrt{\frac{\mathcal{B}(B^0 \rightarrow D_s^{(*)+} \pi^-)}{\mathcal{B}(B^0 \rightarrow D^{(*)-} \pi^+)}} \quad (7)$$

where θ_C is the Cabibbo angle, and $f_{D^{(*)}}$ and $f_{D_s^{(*)}}$ are the meson decay constants.

The $R_{D\pi}$ using $D_s\pi$ is also measured with a data sample of $657 \times 10^6 B\bar{B}$ pairs by Belle[6]. The D_s^+ is reconstructed from $D_s^+ \rightarrow (K^+ K^-)_\phi \pi^+, (K^- \pi^+)_{K^*(892)} K, (\pi^+ \pi^-)_{K_S} K^+$. The obtained branching fraction is $\mathcal{B}(B^0 \rightarrow D_s^+ \pi^-) = (1.99 \pm 0.26(stat) \pm 0.18(syst)) \times 10^{-5}$. Using the fraction, Cabibbo angle[7] $\tan \theta_C = 0.2314 \pm 0.0021$, the lattice QCD calculation of $f_{D_s}/f_D = 1.164 \pm 0.011$ [8] and the fraction $\mathcal{B}(B^0 \rightarrow D^- \pi^+) = (2.68 \pm 0.13) \times 10^{-3}$ [7], we obtain

$$R_{D\pi} = (1.71 \pm 0.11(stat) \pm 0.09(syst) \pm 0.02(theo))\%, \quad (8)$$

where the last term accounts for the theoretical uncertainty in the f_{D_s}/f_D estimation.

The $R_{D^*\pi}$ is measured using $D_s^* \pi$ with a data sample of $657 \times 10^6 B\bar{B}$ pairs by Belle [9]. The D_s^{*+} is reconstructed by D_s^+ combining γ followed $D_s^+ \rightarrow (K^+ K^-)_\phi \pi^+, (K^- \pi^+)_{K^*(892)} K, (\pi^+ \pi^-)_{K_S} K^+$. The yields are extracted from simultaneous fit for above decays. The obtained branching fraction is $\mathcal{B}(B^0 \rightarrow D_s^{*+} \pi^-) = (1.75 \pm 0.34(stat) \pm 0.17(syst) \pm 0.11(\mathcal{B})) \times 10^{-5}$ with significance of 6.1 standard deviation. The third error is from uncertainties in the D_s^+ decay branching fractions. Using the observed fraction, $\mathcal{B}(B^0 \rightarrow D^{*-} \pi^+) = (2.76 \pm 0.13) \times 10^{-3}$, $\tan \theta_C$ [10], and the theoretical estimate of the ratio f_{D_s}/f_D [8], we obtain

$$R_{D^*\pi} = (1.58 \pm 0.15(stat) \pm 0.10(syst) \pm 0.03(theo))\%, \quad (9)$$

where the third error is theoretical uncertainty in the $f_{D_s^+}/f_{D^+}$ estimation. We have assumed that the ratio $f_{D_s}/f_D = f_{D_s^+}/f_{D^+}$. The quenched QCD approximation (heavy quark effective theory) predicts[11] the uncertainty of the assumption about 1%, which is included in the theoretical uncertainty. Uncertainties due to SU(3) symmetry breaking effects[12], which are of order (10–15)%, are not included in the theoretical uncertainty above $R_{D\pi}$ and $R_{D^*\pi}$ with $D_s^{(*)}\pi$ decays.

4 Conclusion

Time-dependent γ analyses in Belle are progressing in Belle. The results from the partial reconstruction method have been updated with a data sample almost twice larger than the previous Belle analysis. Also, the measurements of $R_{D^{(*)}\pi}$ are updated.

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